ELSEVIER
Journal of Volcanology and Geothermal Research 62 (1994) 31–54
Journal of volcanology and geothermal research

Postglacial eruption history of Redoubt Volcano, Alaska

James E. Begét[a], Christopher J. Nye[b]

[a]Department of Geology and Geophysics, University of Alaska, Fairbanks, AK 99775-0760, USA
[b]Geophysical Institute, University of Alaska, Fairbanks, AK 99775, USA

Received 7 May 1992; revised version accepted 20 September 1993

Abstract

Volcaniclastic deposits preserved in valleys on the flanks of Redoubt Volcano comprise a record of the volcano's postglacial eruption history. The oldest and largest deposit is the Harriet Point debris avalanche, emplaced more than 10,500 yr B.P. This debris avalanche travelled more than 30 km down the Redoubt Creek valley to Cook Inlet. About 3600 yr B.P., a massive slope failure of Redoubt Volcano produced at least two lahars that travelled 30 km down the Crescent River valley (Riehle et al., 1981). A series of smaller eruptions between ca. 3600–1800 yr B.P. generated additional lahars and floods that affected the upper Crescent River valley. A pyroclastic fan on the south flank of Redoubt Volcano probably also formed during this time interval. Sometime between 1000 and 300 yr B.P., hydrothermally altered debris collapsed from the summit edifice, and produced a large lahar that travelled more than 30 km down the Drift River valley. At least 5–6 eruptions in the last 250–300 years have produced lahars and floods large enough to impact the site of the Drift River Terminal on the lower Drift River fan. If the eruptive pattern of the last several centuries continues, another eruption is likely sometime in the next 25–100 years.

The Holocene eruptions produced calc-alkaline high-silica andesite and dacite, although quenched andesite and basaltic inclusions record the presence of more mafic magmas. Chemical discontinuities indicate that small, chemically discrete batches of magma fed individual eruptions. Progressive enrichments of highly incompatible trace elements presumably reflect crustal contamination of Holocene magmas.

Keywords: Redoubt volcano, Eruption history, Geochemistry, Debris avalanche, Pyroclastic flow, Lahar, Volcanic hazards

1. Introduction

The record of past eruptive activity at a volcano provides important clues as to the likely nature of future eruptions. Such records often consist of both contemporaneous written documention of historic eruptions and geologic reconstructions of the age and magnitude of prehistoric eruptions (Crandell et al., 1975; Begét, 1981). Reconstructions of the style, frequency, geochemistry, and magnitude of past eruptions over periods of hundreds to thousands of years may reveal patterns in eruptive behavior and suggest the types of hazards that might be associated with future eruptions (Crandell et al., 1979; Begét, 1983; Swanson and Kienle, 1988).

The historic record of eruptive activity at Redoubt Volcano begins with an eruption in 1902 that is known to have produced tephra and local flooding. During 1966–1968, small eruptions of Redoubt Volcano produced tephra, and debris flows and floods swept off the Drift Glacier to

0377-0273/94/$07.00
SSDI 0377-0273(93)E0087-I

inundate the lower Drift River fan (Post and Mayo, 1971; Sturm et al., 1986). The Drift River Terminal, an oil storage, pipeline, and oil tanker loading facility, was constructed on the lower Drift River fan in 1967. The 1989–1990 eruptions of Redoubt Volcano produced widespread ashfalls, and floods and lahars that travelled more than 25 km down the Drift River to Cook Inlet, and impacted the same general area as the 1966 floods (Fig. 1). Large debris flows on January 2 and February 15, 1990, flooded the Drift River Terminal and caused curtailment of the operations of the Cook Inlet Pipeline Company and 10 offshore oil platforms that supplied oil to the terminal (Brantley et al., 1990).

As part of the scientific response to the eruption, we began a study in the summer of 1990 to catalogue deposits of prehistoric Redoubt Volcano eruptions. We report here on our findings concerning the number, extent, and age of prehistoric volcanic flowage deposits preserved in the Drift River, Crescent River, and Redoubt Creek drainages valleys on the flanks of Redoubt Volcano. This report focuses on the stratigraphy, chronology, and geochemistry of volcaniclastic flowage deposits of postglacial age preserved in each of the three major valleys draining Redoubt Volcano. The history of recent tephra eruptions at Redoubt Volcano is described in this volume by Begét and his co-workers, while the postglacial record of tephra eruptions at Redoubt Volcano are the subject of a separate, ongoing investigation and will be described elsewhere.

Our work builds upon several previous studies

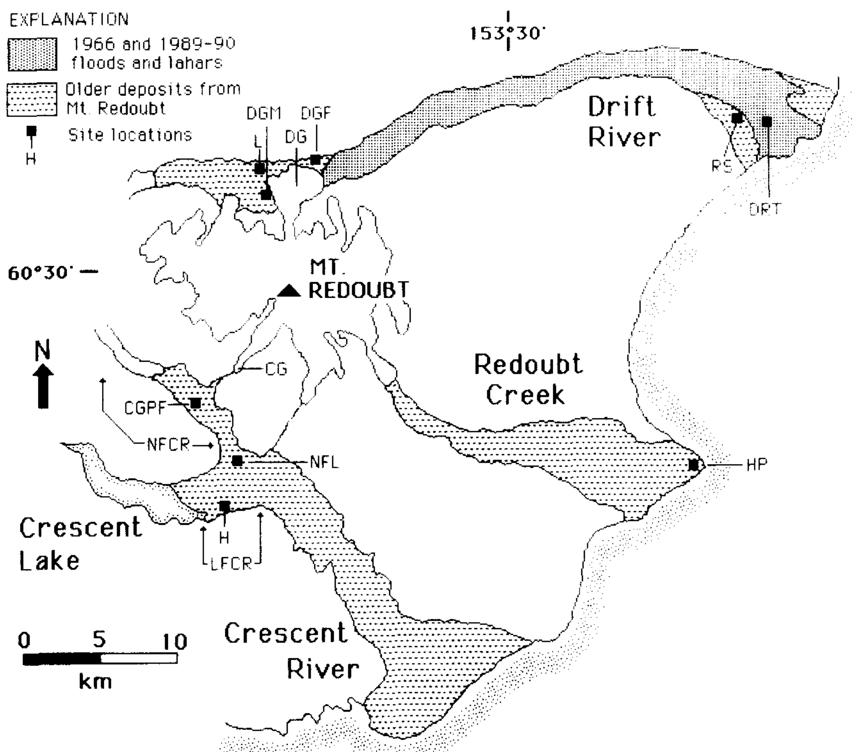

Fig. 1. Major drainages of Redoubt Volcano showing location of features discussed in text, including: *DRT*= Drift River Oil Terminal; *RS*= Rust Slough; *DGF*= Drift Glacier fan; *DG*= Drift Glacier; *L*= lake sediment geologic section; *DGM*= Drift Glacier moraine section; *HP*= Harriet Point; *CGPF*= Crescent Glacier pyroclastic fan; *NFCR*= North Fork of the Crescent River; *NFL*= North Fork Lahars sections; *LFCR*= Lake Fork of the Crescent River, and H = area of mounds. Extent of 1966 and 1989–1990 flood and debris flows from Brantley (1990) and from field studies in 1986 by Begét.

that contain important information on postglacial volcanic deposits in the Redoubt Volcano area. Riehle and Emmel (1980) used photogeologic techniques to map the surficial geology, including flood sediments and lahars, in drainages to the east of Redoubt Volcano, while Riehle et al. (1981) described lahars that travelled from Redoubt Volcano down the Crescent River drainage to Cook Inlet. Till et al. (1990) made a preliminary evaluation of the volcanic hazards of Redoubt Volcano, based on its behavior prior to the 1989–1990 eruptions, and Brantley (1990) briefly summarized what was known of the eruption history of Redoubt Volcano.

2. Postglacial volcaniclastic deposits from Redoubt Volcano

2.1. Harriet Point debris avalanche

A previously unrecognized debris avalanche deposit from Redoubt Volcano covers almost 40 km^2 in the lower Redoubt Creek area (Begét and Nye, 1990). We name this deposit the Harriet Point debris avalanche for excellent exposures in sea-cliffs near Harriet Point (Figs. 2, 3). The deposit forms a light-yellow to gray bouldery, hummocky layer 5–15 m thick that can be traced in outcrops along almost 7 km of sea cliffs north of Redoubt Creek. The yellowish avalanche deposit typically overlies gray clays and silt of late Pleistocene age, which appear in part to consist of the Bootlegger Cove Clay (Riehle and Emmel, 1980). The avalanche itself is overlain in most places by 1–2 m of peat containing several thin tephra layers. In a few areas, particularly on the northeast border of the deposit, it is overlain by coarse alluvium.

The sedimentology and physical characteristics of the Harriet Point debris avalanche deposits are similar to those of the 1980 Mount St. Helens debris avalanche (Glicken, 1991) and other large volcanic debris avalanches around the world. The Harriet Point debris avalanche consists primarily of angular volcanic cobbles and boulders dispersed in an unconsolidated matrix of coarse sand and granule-sized debris, although zones of finer material are also present. Examination of the deposit at several sites indicated that the coarse material and the matrix typically consists of 95–100% volcanic clasts. The clasts are densely fractured and very angular. Some discrete lithologic zones within the deposit appear to consist of single, large, shattered volcanic rocks. Isolated voids and zones of openwork are found between many clasts and are characteristic of zones of coarser material.

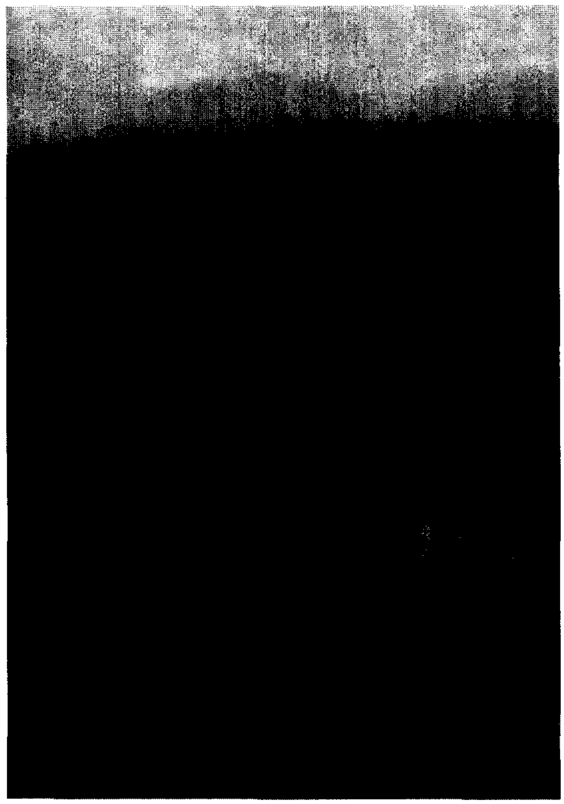

Fig. 2. Area of hummocky topography formed by the Harriet Point debris avalanche near Harriet Point. Trees and brush grow preferentially on well-drained mounds, while boggy meadows are found between the mounds. Note ca. 10-m-high avalanche hummocks capping wave-cut cliffs in the foreground, overlying fine- grained Pleistocene sediments.

While most of the larger clasts in the Harriet Point debris avalanche consist of fresh-appearing andesite and dacite, some clasts within the deposit are coated with yellow to red sand, silt and clay, and entire clasts in some areas appear to be deeply oxidized and hydrothermally al-

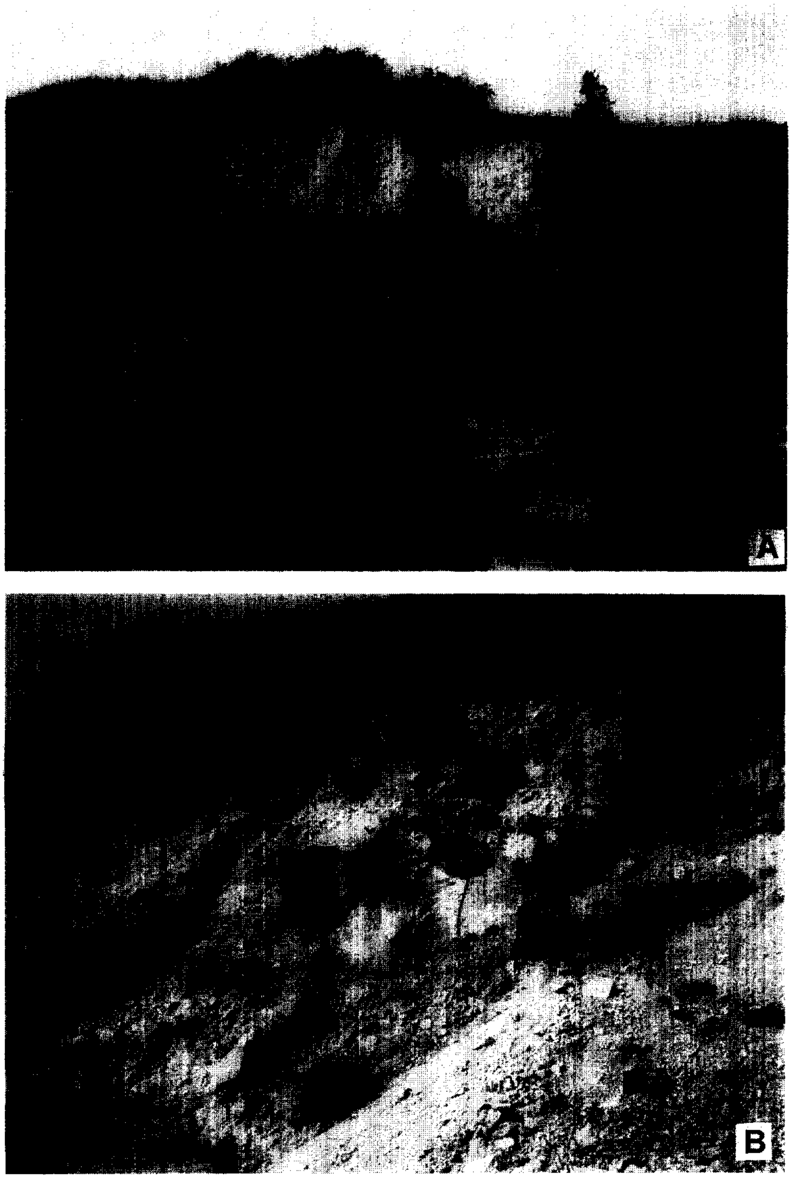

Fig. 3. (A) Beach exposure through 8-m-high hummock of Harriet Point debris avalanche deposit found approximately 100 m south of Harriet Point, overlying fine-grained Pleistocene lacustrine sediments. Note the numerous volcanic boulders on the beach derived from the avalanche deposit. (B) Extremely coarse and fine textural zones of varying volcanic lithology are juxtaposed within the Harriet Point debris avalanche deposit. Note highly angular character of large clasts, and open fracture in large boulder to left of geologist.

tered. The areas of highly colored, hydrothermally altered material generally have sharp contacts with adjacent zones of fresh-appearing gray andesite, which suggests the alteration did not occur in situ. A hydrometer analysis of a sample taken from a zone of altered debris indicated it consisted of 71% sand, 18% silt, and 11% clay, while X-ray diffraction analysis of the clay fraction showed that it consisted entirely of smectite group clays. A similar predominance of smectite group clays, including montmorillinite, has been reported from hydrothermally altered zones in other volcanic debris avalanches, such as those at Mt. Rainier (Crandell, 1971). An extensive area of hydrothermally altered volcanic rock has been reported from the upper slopes of Redoubt Volcano, at the head of the modern Redoubt Creek drainage (Till et al., 1990), in the likely source area of the Harriet Point debris avalanche.

At least some of the larger clasts in the deposit are broken by complex jagged or curved open fractures. Such "jigsaw" fractures have been noted in other debris avalanches and are thought to form as a result of inter-clast impacts during transport and emplacement (Ui and Glicken, 1986; Ui et al., 1986).

Several types of discrete textural and lithologic zones occur within the deposit, and were exposed as irregularly shaped pods of volcanic debris from ca. one to several meters in diameter in 1991 at the seacliffs at Harriet Point. Some lithologically homogeneous zones appeared to consist of fractured lithic blocks or portions of lava flows while other areas were characterized by red, yellow, or white hydrothermal alterations. A few areas of the seacliff exposure were composed of coherent regions of bedded, tuffaceous volcanic material. Some other zones and the bulk of the deposit matrix appeared to consist largely of well-mixed, comminuted volcanic debris. The contacts between the textural zones commonly appeared sheared and deformed, and clasts at the borders of the zones were sometimes broken, with the fragments adjacent to the margin of the textural zone being displaced or re-oriented. Similar features were common in the 1980 Mount St. Helens debris avalanche sediments, and are thought to be characteristic of debris avalanche deposits (Siebert et al., 1987; Glicken, 1991). Such textural zones are generally interpreted as packages of rock debris from the source volcano that retained their coherence during transport and emplacement.

The Harriet Point debris avalanche is found in a glaciated area but is readily distinguished from glacial till. The grain-size distribution of the Harriet Point debris avalanche is in good agreement with that reported for other debris avalanches and lacks the fine-grained component that characterizes the matrix of glacial till (Fig. 4). The absence of fine-grained material, except in the zones of hydrothermal alteration, is particularly striking since the clays found underlying the debris avalanche deposit at Harriet Point would have been reworked by glaciers. The lithologic makeup of the deposit also precludes a glacial origin. While virtually all boulders and the majority of the cobbles in glacial till in nearby areas consist of granitic or crystalline metamorphic rocks, such lithologies are almost entirely absent from the avalanche deposit. Also, no striations or polished, abraded surfaces were observed on clasts in the debris avalanche, although such are common in glacial deposits. Similarly, the sand-rich matrix of glacial deposits and alluvium found in valleys near Redoubt Volcano, including those in moraines found farther up Redoubt Creek, contain abundant quartz, micas, and other non-volcanic clasts while the avalanche deposit matrix contains virtually no such material.

The Harriet Point debris avalanche is poorly exposed in areas away from the sea- cliffs, but its areal extent can be determined from the distribution of large hummocks found over much of its surface. These hummocks typically form individual and coalescent elongate ovals that are from ten to hundreds of meters in diameter and as much as 20–30 m in height. The size of these hummocks is consistent with those found at de-

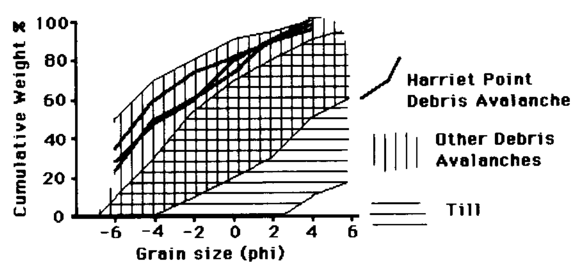

Fig. 4. Grain size analyses of the Harriet Point Debris avalanche compared with other debris avalanches and glacial till. The Harriet Point deposit is similar to other coarse-grained debris avalanches, but is significantly coarser than glacial till. Grain size field for debris avalanches from Siebert (1984) and for glacial till from Flint (1971).

bris avalanches of similar size at other volcanoes (Fig. 5).

At its outlet to Cook Inlet, Redoubt Creek has incised its channel almost 100 m into the debris avalanche and underlying Pleistocene sediments, and isolated small terrace remnants can be found along it. These terraces may record transient postitions of the river during downcutting, or they may have been formed by small eruptions that postdate the Harriet Point debris avalanche. A large moraine in the central reaches of Redoubt Creek truncates the debris avalanche on its upstream side, and apparently postdates it. Some or all of the terraces along lower Redoubt Creek may reflect fluvial downstream aggradation and erosion during this alpine glacier advance.

Offshore from Harriet Point, bathymetric data show many submarine hills of about the same size as the debris avalanche hummocks occurring beneath Cook Inlet about 3–5 km east of the current shoreline (Fig. 6). Much of the nearshore submarine topography appears smooth, but this may reflect long-term deposition of glacial sediment from upper Redoubt Creek and modification by the strong tides of Cook Inlet. If these submarine hills are hummocks deposited by the Harriet Point debris avalanche, then it originally extended at least 5 km beyond the modern shoreline, and its total travel distance was about 35 km.

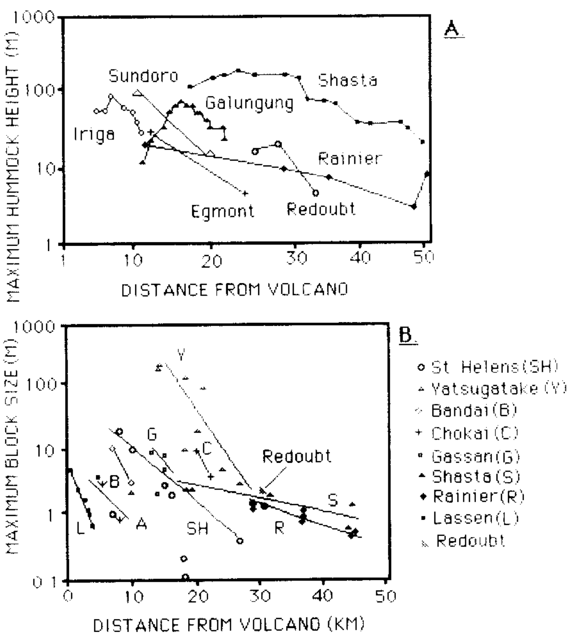

Fig. 5. (A) Maximum hummock height vs. distance from source volcano for Redoubt Volcano and other large volcanic debris avalanches. (B) Maximum block size versus distance from source volcano for Redoubt Volcano and other large debris avalanches. Data for the Harriet Point avalanche is only available from beach exposures. Selected data from Ui (1983) and Siebert (1984).

The Harriet Point debris avalanche is the largest and most extensive such deposit known associated with any Cook Inlet or Alaska Peninsula volcano. Several debris avalanches have been mapped at Augustine Volcano, but these travelled no more than 8–12 km (Siebert et al., 1987; Begét and Kienle, 1992). A large prehistoric debris avalanche preserved south of Spurr Volcano travelled about 20 km (Nye and Turner, 1990).

It is not possible to accurately estimate the original volume of the Harriet Point deposit as it has been completely eroded away near Redoubt Volcano where it was probably originally the thickest. However, a comparison of its areal extent to that of the less extensive 1980 Mount St. Helens avalanche suggests it may originally have been of similar or somewhat greater volume (Fig. 7). The Mount St. Helens avalanche deposited about 2.8 km^3 of debris (Glicken, 1991).

The Harriet Point debris avalanche must be no older than latest Pleistocene in age, as it clearly postdates the deglaciation of much of Cook Inlet, including the lower Redoubt Creek drainage ca. 14–15 kyr B.P. (Hamilton and Thorson, 1983; Schmoll and Yehle, 1986). The avalanche deposit overlies clays and silt thought to correlate with the Bootlegger Cove Formation (Riehle and Emmel, 1980). The Bootlegger Cove Clay has been dated at other localities to ca. 13–15 kyr B.P. (Schmoll et al., 1972).

Several radiocarbon dates were obtained from peat sections that immediately overlie the avalanche near Harriet Point (Table 1). The oldest date was 10,460 ± 80 yr B.P., obtained from a horizon separated from the avalanche by 10–20 cm of silt. There was no soil development visible below the peat, within the silt, or on the ava-

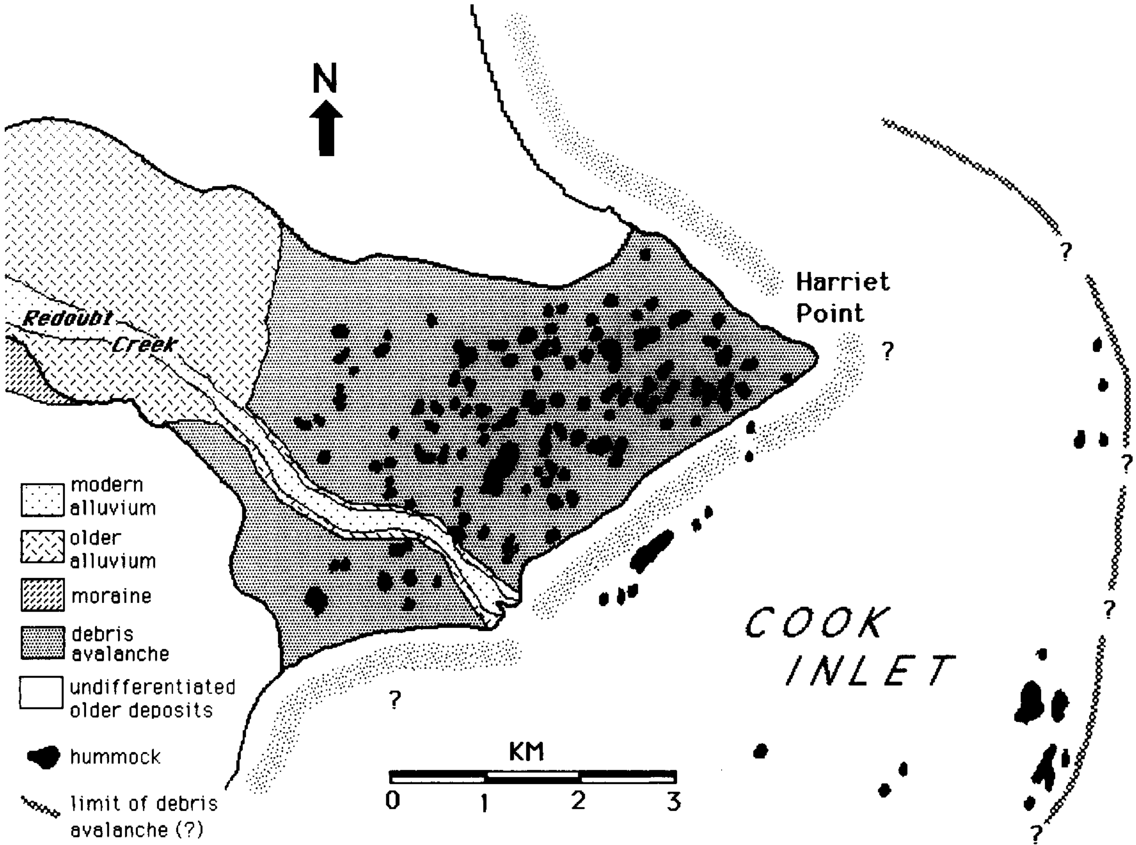

Fig. 6. Generalized geology of the Harriet Point area, lower Redoubt Creek. Debris avalanche hummocks (in black) taken from aerial photos for sub-aerial exposures, and from bathymetry for possible submarine extent of the debris avalanche.

lanche surface, which suggests that this date constitutes a close upper limiting age. The available data therefore suggest the Harriet Point debris avalanche was deposited sometime between 10.5 and 13 kyr B.P.

2.2. Crescent River lahars

At least two clay-rich mudflows, known as the Crescent River lahars, travelled 30 km down the Crescent River valley to the coast of Cook Inlet, buried an area of almost 90 km^2, and had an original volume of more than 400×10^6 m^3 (Riehle et al., 1981). Both lahars contain significant amounts of hydrothermally altered rock debris, have compact clayey matrices, and are generally olive-gray to yellow to red in outcrop. The upper lahar locally contains a component of fresh-appearing gray andesitic silt, sand, and granule size material. Wood fragments incorporated in the lahars are not burned, although some appear slightly charred on their outer edges. Prismatically jointed blocks are present in some exposures.

The age of the Crescent River lahars can be closely determined. Small, isolated wood fragments in the lower lahar have previously been dated at 3605 ± 145 and 3450 ± 140 yr B.P. (Riehle et al., 1981). A large tree still in growth position but inundated and broken off 2 m above its base by the lower lahar was exposed by wave erosion in 1990. Wood from the outer rings of this tree dates to 3620 ± 70 yr B.P. (Table 1). If taken together and averaged, the three dates on wood from the lahars suggest an age for this deposit of 3589 ± 58 yr B.P., while an average of

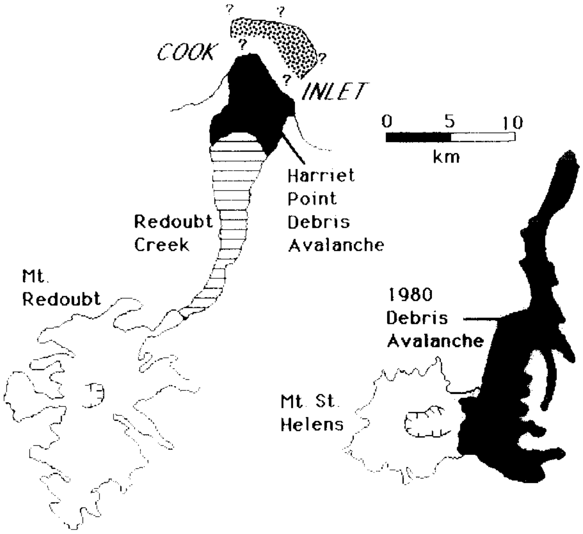

Fig. 7. Comparison of the area of the late Pleistocene Harriet Point debris avalanche at Redoubt Volcano and the 1980 debris avalanche at Mount St. Helens. The lined pattern in Redoubt Creek shows the extent of post-avalanche glacial and fluvial erosion in upper Redoubt Creek. The possible submarine extent, suggested by bathymetry in Cook Inlet, is indicated by patterned area within Cook Inlet.

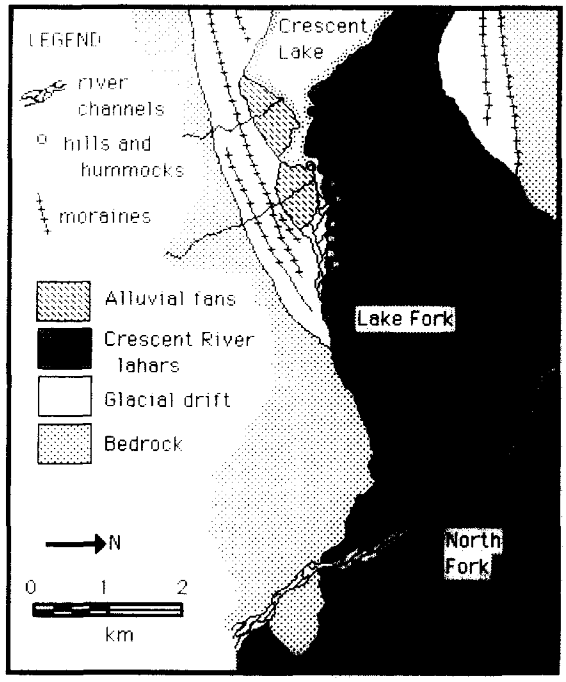

Fig. 8. Inferred original extent of the Crescent River lahars, and location of small mounds near the outlet of Crescent Lake. These mounds occur near an area of hummocky topography associated with moraines that border Crescent Lake, and may in part consist of glacial deposits. The Crescent River lahars are largely buried by the younger North Fork lahars.

the two apparently concordant dates yields 3617 ± 63 yr B.P. Thus, the lower Crescent River lahar appears to date to about 3600 yr B.P., corresponding to a calibrated age between 3963 and 3875 calendar years ago (Table 1). There is no soil development visible between the upper and lower lahar, and the contact is sharp and conformable at several excellent exposures in sea cliffs, which suggests that the upper lahar was deposited very soon after the lower lahar.

The Crescent River lahars form a widespread valley fill in the lower Crescent River valley, and apparently backfill the major valley downstream from Crescent Lake. Approximately a dozen mounds rise above the surface of the valley fill along a 2-km reach of the Crescent River near the outlet of Crescent Lake in an area located 20 km southwest of Redoubt Volcano. These mounds were initially interpreted as coherent blocks of volcanic material transported by the Crescent River lahars from Redoubt Volcano; a similar, isolated block incorporated in a lahar is found far downstream in the coastal seacliffs (Riehle et al., 1981, fig. 5). Subsequently, Brantley (1990) and Till et al. (1990) noted that these mounds resemble hummocks of the 1980 Mount St. Helens debris avalanche.

We made a reconnnaissance study of the area of the mounds at the outlet of Crescent Lake in order to determine if they were part of an ancient debris avalanche. The mounds are highly vegetated and poorly exposed, and we were unable to closely examine the character of the sediment in the mounds. However, they occur only several hundred meters north of a set of lateral moraines and an area of hummocky glacial drift that forms the southern border to Crescent Lake. These moraines may have impounded Crescent Lake prior to any Redoubt Volcano eruptions (Fig. 8). It is possible that some of the mounds near Crescent Lake are actually glacial deposits, although others clearly consist of laharic material (Riehle et al., 1981, p. 4).

The restricted distribution of the mounds

Table 1
Radiocarbon dates associated with postglacial volcanic deposits at Redoubt Volcano

Date	Lab no.	Sample no.	Material dated	Significance
210±50	B-40780	90MR-81-3	wood	Upper limiting date, yellow lahar in lower Drift River
260±60	B-41936	90MR-80-1	soil	Upper limiting date, yellow lahar, lower Drift River
1060±70	B-40791	90MR-81-1	soil	Lower limiting date, yellow lahar, lower Drift River
1630±70	B-41933	90MR-64-18	peat	Upper limiting date, youngest major tephra at western coast peat section
1840±50	B-41934	90MR-64-18	peat	Upper limiting date, lahars in Crescent River
2080±60	B-40789	90MR-57-5	soil	Lahars and tephra, Crescent River valley
2230±60	B-40779	90MR-73-7	peat	Upper limiting date, major tephra Crescent River valley
2270±70	B-40786	90MR-60-5	peat	Upper limiting date, major tephra
2930±60	B-40782	90MR-73-8	peat	Limiting date on tephra, Crescent River valley
3120±60	B-40788	90MR-60-2	peat	Limiting date on tephra
3320±70	B-40785	90MR-64-17	peat	Upper limiting date on tephra
3410±60	B-40778	90MR-71-4	peat	Upper limiting age, major tephra in Crescent River valley
3620±70	B-40777	90MR-73-1	log	Crescent River lahar
3890±70	B-40783	90MR-64-11	peat	Lower limiting age on pumice eruption
4840±70	B-40787	90MR-64-10	peat	Limiting date on tephra
6340±80	B-40790	90MR-64-9	peat	Limiting date on tephra
6660±90	B-40792	90MR-64-8	peat	Limiting date on tephra
7730±160	B-41935	90MR-70-2	soil	Upper limiting date, major tephra near lower Drift River
10460±80	B-40781	90MR-64-3	peat	Upper limiting age, Harriet Point debris avalanche

seems inconsistent with a debris avalanche origin. We found no mounds or debris avalanche deposits while examining continuous 10–30-m-high exposures along more than 15 km of the Crescent River. The surface of the lahar fan in the upper Crescent valley forms a broad flat surface several kilometers wide, but we found no clusters of mounds protruding through this surface anywhere except near Crescent Lake. Studies of aerial photos and our own field observations show that no hummocks or mounds exist anywhere on the 15-km-long lower Crescent River fan, where the valley has a low gradient and a debris avalanche should come to rest. At the coastline numerous seacliff exposures expose the base of the Crescent lahars, but no debris avalanche deposit was found by excavation or during a reconnnaissance aerial survey of more than 10 km of continuous beach-cliff exposure of the Crescent River lahars. We also found no mounds or debris avalanche deposits in examinations of postglacial sediments in the valleys and slopes on the southwest sides of Redoubt Volcano.

The clay-rich lower lahars in the Crescent River valley resemble water-mobilized deposits formed from massive slope failures of hydrothermally altered material from the upper slopes of volcanoes (Crandell, 1971). The dozen or so isolated mounds near Crescent Lake may consist of coherent blocks of volcanic material incorporated and then rafted in the Crescent River lahars during a collapse of the southern flank of Redoubt Volcano. The transport of a single block of stratified alluvial sediments more than 30 km to the shores of Cook Inlet clearly demonstrates the competence of the lower, clay-rich Crescent River lahars, and their ability to transport blocks of apparently fragile debris (Riehle et al., 1981). The

Crescent River lahars appear to have raised the level of Crescent Lake by partly overtopping a pre-existing glacial dam.

2.3. North Fork Lahars

Several lahars, tephra layers, and beds of alluvium separated by peat layers and thin soils are exposed in 10–30-m-high streamcuts along the North Fork of the Crescent River. These deposits record eruptions of Redoubt Volcano that are younger than the Crescent River lahars and that strongly affected the upper parts of the Crescent River drainage. We refer to this newly recognized set of deposits as the North Fork lahars (Fig. 1).

Together these laharic deposits form a flat-topped valley fill that occupies virtually the entire upper Crescent River valley. The surface gradient of the valley fill is about 0.01–0.02 near the confluence of the Lake Fork and the North Fork of the Crescent River; when traced upvalley it merges into a steeper fan with a gradient of as much as 0.2 that debouches from the central of three valleys on the southwest flank of Redoubt Volcano. This valley directly drains the summit region of Redoubt Volcano, and was apparently the primary source of the North Fork lahars, although some of the material may have come down the other valleys from the summit of Redoubt Volcano.

Numerous exposures through the valley fill expose as many as 4–6 separate yellow to gray lahars composed primarily of fresh lithic fragments. These monolithic lahars are typically 1–3 m thick (Figs. 9, 10). The North Fork lahars typically have a coarse sand-sized matrix and contain many andesitic clasts 50–100 cm or more in diameter, and so are much more coarse grained than the clay-rich lahars found downstream. One thick lahar exposed for several kilometers in stream cuts near the confluence of the North Fork and Lake Fork contained numerous prismatically jointed blocks, which were apparently hot when emplaced. Some clasts in this lahar had reddish hydrothermally altered rinds, while others were surrounded by rings of reddish hydrothermal alteration in the enclosing fine-grained lahar sediment. We believe this lahar consisted in part of still-hot pyroclastic flow debris or col-

Fig. 9. Exposure of the North Fork lahars near the confluence of the Lake Fork and North Fork of the Crescent River. Note 2–3-m-thick coarse-grained debris flows exposed at the base of the streamcut, and tephras (white horizons) interbedded with alluvium and thin lahars at the top of the exposure. Helicopter and geologist in the center of the photograph illustrate scale.

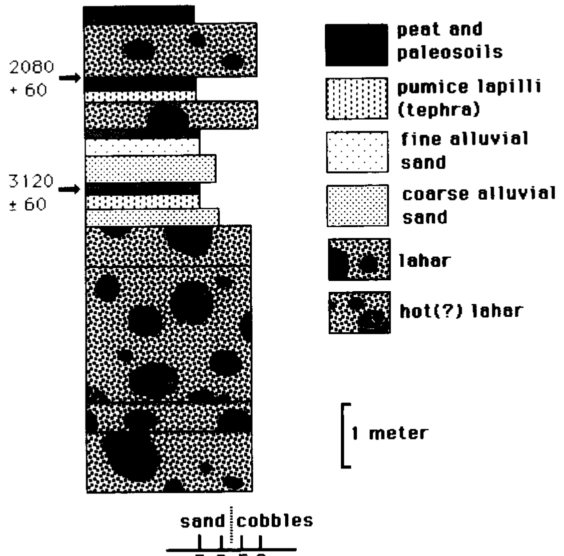

Fig. 10. Stratigraphy of North Fork lahar deposits near the confluence of the Lake Fork and North Fork of the Crescent River. All lahars consist mainly of unaltered dacite and andesite fragments. Radiocarbon dates on peat layers between sets of lahars, tephra layers, and alluvium indicate these deposits record eruptions that continued for at least 1500 years after the emplacement of the Crescent River lahars.

lapsed dome rocks. The other lithic lahars exposed along the upper Crescent River probably also consist largely of reworked pyroclastic debris, although evidence of heat is only rarely encountered.

At least three sets of deposits of younger alluvium, lahars, and tephra can be recognized above the sequence of thick lahars (Figs. 9, 10). The upper thin lahars also appear to be monolithologic, and contain matrix-supported clasts as much as 20–50 cm in diameter, and consist almost entirely of gray andesite. These sediments resemble deposits laid down in the lower Drift River valley during the 1966 and 1989–1990 eruptions, and may have been produced when small pyroclastic flows were emplaced over snow and glaciers. Radiocarbon dates of 2080 ± 60 and 1840 ± 50 yr B.P. on peat layers interbedded with the youngest lahars in the upper Crescent river valley suggest that eruptions affected the Crescent River valley for almost two thousand years after the time of the Crescent River lahars. Radiocarbon dates of 1630 ± 70, 2230 ± 60, 2270 ± 70, 2930 ± 60, 3120 ± 60, 3320 ± 70, 3410 ± 60 yr B.P. on peat adjacent to tephra layers of fine to medium lapilli exposed in coastal bluffs 30 km east of Redoubt Volcano also show that pyroclastic eruptions continued for more than 1800–2000 years after the time of the Crescent River lahars (Table 1). The base of the North Fork lahar sequence is not exposed anywhere along the upper river, but the two clay-rich Crescent River lahars exposed in beach cuts 20 km downstream presumably underlie the multiple North Fork lithic lahars found nearer to the volcano.

2.4. Crescent Glacier pyroclastic fan

A large and previously unrecognized fan of pyroclastic flow debris is preserved in the upper reaches of the North Fork of the Crescent River, just where the valley fill fan debouches from the upper slopes of Redoubt Volcano. We informally refer to this previously unrecognized assemblage of pyroclastic flow deposits as the Crescent Glacier pyroclastic fan, as the flows descended directly over the large, informally named "Crescent Glacier" from the summit (Fig. 1). The surface of the fan grades into the broad fill of the North fork lahars found just downvalley, and reworking and erosion of this set of pyroclastic flows may have been the source of some or all of the North Fork lahars found just downvalley. Unfortunately, the available exposures were too incomplete to allow us to trace the deposits of the Crescent Glacier pyroclastic fan directly to the North Fork lahars exposed in stream cuts a few kilometers downvalley.

The pyroclastic fan itself is best exposed in a 100-m-long and 25-m-high stream cut located just east of the confluence of the North Fork of the Crescent River and the outlet stream from the "Crescent Glacier". At this point it consists of more than a dozen stacked and horizontally bedded lithic 1–3-m-thick pyroclastic flows (Fig. 11). Thinner beds of sandy, crossbedded surge deposits locally separate the main pyroclastic flows. Highly angular and prismatically jointed andesite blocks and bombs were very common

Fig. 11. Assemblage of more than a dozen dacitic pyroclastic flows in the Crescent Glacier pyroclastic fan exposed in a 25-m-high streamcut in the upper Crescent River valley (see Fig. 1 for location). Geologist at the base of the exposure gives scale.

within the flows, and formed a rubbly talus at the base of the cliff. The Crescent Glacier pyroclastic fan indicates that during at least one Holocene interval, multiple pyroclastic flows travelled at least 12 km from the volcano summit to the North Fork of the Crescent River valley at the base of the volcano, and produced a thick fan of pyroclastic flows. These "Merapi type" block and ash flows were probably generated during one or more sustained episodes of dome growth. The Crescent Glacier pyroclastic fan was erupted following the major episode of slope failure recorded by the clay-rich Crescent River lahars found in the lowermost Crescent River valley. Summit dome eruptions apparently reconstructed the southern part of the summit edifice of Redoubt Volcano, as today there is no visible crater or scar on the south slope or summit of Redoubt Volcano that could have been the source of the more than 400×10^6 m^3 of material found in the clay-rich Crescent River lahars.

2.5. *Rust Slough lahar and recent flood deposits*

An assemblage of young flood deposits and a slightly older lahar are exposed in stream cuts along Rust Slough, only a few kilometers to the southwest of the Drift River Terminal (Fig. 11). The basal lahar in this assemblage was exposed just at the 1990 water level along Rust Slough, is commonly yellow to red, and is referred to here as the Rust Slough lahar. It consists primarily of highly oxidized and altered lithic clasts in a clayey matrix of hydrothermally altered material and is 2–3 m in thickness (Fig. 12). The abundance of hydrothermally altered material suggests that this deposit records a partial collapse of part of a prehistoric summit edifice of Redoubt Volcano. The reddish color of the waters in Rust Slough may in part reflect the leaching of iron oxides and the erosion of yellow and reddish clays from stream cuts through this deposit. This thick lahar is exposed for several kilometers along upper Rust Slough, but probably underlies a much larger area of the Drift River fan where it has been buried by younger deposits.

A 2–4-cm-thick peat horizon buried by the Rust Slough lahar was dated at 1060 ± 70 yr B.P. (Table 1). The peat overlies thinly bedded alluvium that is locally as much as 2 m thick, and extends below the current level of Rust Slough. The yellow lahar itself is overlain by as much as 2 m of alluvium that has buried a thin soil and peat horizon developed on the surface of the Rust

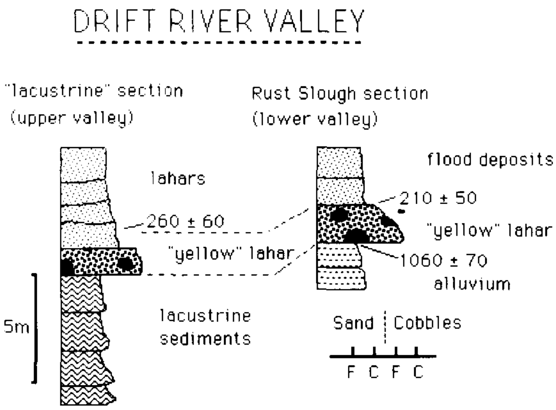

Fig. 12. Measured sections through the Rust Slough lahar at Rust Slough, and a similar lahar composed of yellow, hydrothermally altered volcanic debris at the lake sediment section northwest of the Drift Glacier. Radiocarbon dates from both sections are consistent with a correlation between these two deposits.

Slough lahar. Tree stumps as much as 30 cm in diameter are preserved in growth position above the yellow lahar; one stump was dated at 260 ± 60 yr B.P. and provides an upper limiting date on the underlying yellow lahar. A concordant upper limiting date was obtained from a similar site in the upper Drift River valley (see below).

At least two younger sandy units, each from 50 to 100 cm thick, comprise the alluvium exposed above the yellow lahar. These units appear similar to the massive sandy alluvium deposited by the 1966 and 1989–1990 eruptions and are interpreted here as hyperconcentrated flood deposits. Coeval lahars associated with these flood sediments may have been confined to the main Drift River channel. A second, buried soil horizon with occasional small, broken and abraded logs and small stumps separates the two sandy flood deposits, and a well-developed forest with large trees is present at the modern ground surface. Tree coring showed that some of the large trees in the lower Drift River valley are ca. 80 years old, and thus this youngest deposit may have been produced by the 1902 eruption or a slightly older eruption of Redoubt Volcano.

The 1966 and 1989–1990 eruptions of Redoubt Volcano caused widespread aggradation from valley wall to valley wall along the middle reaches of the Drift River, so that there are few exposures of older deposits found upvalley from the Drift River fan to the area of the Drift Glacier, some 30 km upvalley. About 1.5 km northwest of the terminus of the Drift Glacier, a 10-m-thick set of lacustrine deposits along the upper Drift River consists of at least four normally graded beds, each 1–2 m thick (Till et al., 1990). These lacustrine deposits appear to record damming of the Drift River valley by the Drift Glacier. The repetitive cycles of normally graded sedimentation were probably formed by successive fillings of the upper Drift River valley, perhaps punctuated by catastrophic lake drainings (jökulhlaups) through the ice dam (Sturm et al., 1986, 1987).

There are isolated and rounded pumice lapilli in the lake- sediment section, but no deposits of airfall tephra layers or pyroclastic flows, which suggests they formed during a dormant interval at Redoubt Volcano. The apparent existence of a Drift Glacier dam of the upper Drift River valley also suggests a period without major eruptions. The 1966 eruptions largely destroyed the upper parts of the Drift Glacier, and produced a prolonged period of stagnation that stopped an advance that might have dammed the upper Drift River. The Drift Glacier had largely reformed by the late 1980s and was advancing again (Sturm et al., 1986), but the 1989–1991 eruptions again removed its upper parts. Similar destruction of the glacier by eruptions almost certainly did not occur during this prehistoric interval when it was large enough to dam the upper valley.

The lake sediments are overlain by a ca. 1-m-thick, clay-rich yellow lahar, and a similar deposit of yellow, hydrothermally altered clayey debris is locally exposed in stream cuts for more than hundred meters along the Drift River downstream from the lacustrine section. This distinctive yellow lahar is thought to be correlative with the thick yellow lahar found at Rust Slough. Both overlie non-volcanic deposits, as the upper lahar rests upon the lacustrine sequence, while the clayey lahar at Rust Slough overlies thinly bedded alluvium. In addition, a thin soil above the yellow lahar at the lake sediment section was dated to 210 ± 50 yr B.P., close to the date of 250 ± 60 yr B.P. on wood from above the clayey yellow lahar at Rust Slough (Fig. 12). The very weak soil development on this deposit suggests it is not much older than the radiocarbon dated soil, so that this widespread clay-rich lahar appears to record a massive slope failure of hydrothermally altered debris from the north side of Redoubt at ca. 200–400 yr B.P.

The presence of the Rust Slough lahar near the Drift River Terminal more than 30 km downvalley from Mount Redoubt indicates this deposit was originally quite extensive. We cannot directly reconstruct its areal extent and volume, as the Rust Slough lahar has been largely buried by younger lahars and flood deposits. However, if a distribution similar to the flood deposits of the 1989–1990 eruption is assumed, its original volume may have been on the order of 100–200×10^6 m^3. For comparison, the volume of the Crescent River lahars has been estimated at 435×10^6 m^3 (Riehle et al., 1981). The modern summit basin, partly exposed by melting of the upper Drift Glacier during the 1989–1990 eruptions, is about 200–250 m deep, open to the north, and has a volume of about 100×10^6 m^3. Perhaps this crater reflects a massive slope failure several hundred years ago that produced the Rust Slough lahar.

A prehistoric pyroclastic flow deposit is exposed between two horizons of till in a stream cut through moraines just west of the piedmont lobe of the Drift Glacier (Fig. 1). The 1–2-m-thick flow rode up a steep, 10-m-high slope cut on the older moraine, and is truncated and buried by a younger moraine. These are the innermost moraines of the Drift Glacier, lying only a few hundred meters beyond its current border. They were probably deposited during the Little Ice Age of the 16th–19th century, so that the intercalated pyroclastic flow is also probably only a few hundred years old.

Still younger volcaniclastic deposits found in the upper Drift River valley may correlate with the younger, hyperconcentrated flood deposits found above the yellow lahar at Rust Slough. At the lake sediment section, as much as 4 m of coarse sandy andesitic debris, consisting of at least 3–4 separate lahar or pyroclastic flows, lies above the yellow lahar and the thin soil developed upon it. This material was deposited by mobile flows that climbed and overtopped the 10-m-high lake sediment section, but at least the basal flow apparently was not hot when emplaced, as the underlying soil is not charred. Deposits of the 1989–1990 eruptions overlie a weak soil developed on these lahars, suggesting they were formed in 1902 or perhaps in slightly older eruptions.

Thick sections of coarse-grained fluvial material are exposed in a 15–20-m-thick fan preserved just north of the Drift River and below the terminus of the Drift Glacier. These lithologically heterogeneous deposits appear to consist mainly of coarse glacial outwash, although it is possible that some of the coarse alluvium was produced during draining of ice-dammed lakes in the upper Drift River valley. Recent pyroclastic flow deposits are also intercalated in the fan material. Some beds of cobble- and boulder-rich alluvium contain rare prismatically jointed blocks, while at least two pyroclastic flow deposits, each ca. 2 m thick, can be traced for 20–30 m across the lower and upper parts of the fan. The age of this fan is not known, but it appears to be very young as there is little soil development or ash on its surface. It predates the 1966 eruption, and may date to the 1902 eruption or an earlier, prehistoric event.

3. Geochemistry of Holocene volcanic deposits

Major- and trace-element analyses of juvenile magmatic samples from the sequence of Holocene deposits erupted by Redoubt Volcano were obtained to determine if there were systematic chemical changes with time (indicative of a progressive evolution of the magmatic plumbing system) or discrete chemical changes (indicative of major temporal discontinuities) in the magmatic system. Geochemical analyses were made of five prismatically jointed blocks and an inclusion collected from the Crescent River lahars, juvenile dome fragments from one of the North Fork hot lahars, a juvenile block from the Crescent Glacier pyroclastic fan, seven prismatically jointed blocks and seven inclusions from young pyroclastic flows in the fan at the base of the Drift Glacier, and 29 coarse Holocene pumice samples from tephra pits surrounding the volcano. Thirteen samples of prehistoric cone-building lavas were also analyzed (Table 2).

Holocene ejecta at Redoubt Volcano were all calc-alkaline silicic andesites and dacites (Fig. 13). Major-element compositions are broadly similar to other eastern Aleutian magmas except for their slightly higher FeO_t/MgO ratios (~ 2.5 vs. ~ 1.5 at 60% SiO_2). Most Holocene Redoubt Volcano ejecta have between 58 and 63.5 wt.% SiO_2 and are more silicic than Pleistocene cone-building flows, extending the trend towards eruption of progressively more silicic compositions observed through the last few hundred thousand years (Till et al., 1994-this volume).

Mafic Holocene magmas, with SiO_2 values as low as 51%, were represented only by quenched andesite and basalt inclusions found in juvenile blocks. These inclusions resemble the early cone-building basalt flows, and may record episodic injection of more mafic magma into the upper level magma storage system during the Holocene.

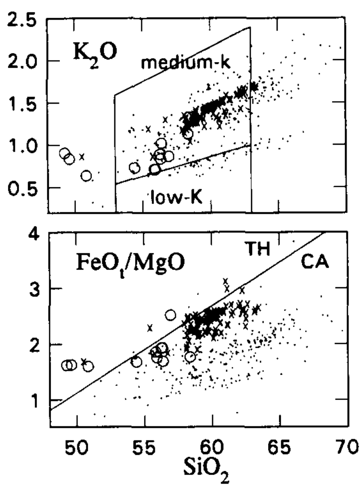

Fig. 13. Analyzed values of K_2O and FeO_t/MgO versus SiO_2 for Holocene volcanic rocks from Redoubt Volcano (solid x), early and late cone-building lavas (open circles), and published analyses of samples from other nearby volcanoes of the Alaska Peninsula (dots). Holocene magmas occupy the higher SiO_2 range of the Redoubt array. K_2O contents are similar to those of other eastern Aleutian arc samples except for those that are transitional low-K to high-K from Augustine Volcano. Redoubt lavas have slightly elevated FeO/MgO compared to other eastern Aleutian arc samples.

Trace-element variations for the Holocene samples were normalized relative to Redoubt basalt 90NR14, a representative cone-building flow (Fig. 14). For most elements there is a high degree of consistency among samples of various ages, both in absolute and relative elemental abundances. Rare Earth Element (REE) patterns are slightly concave-up, with the light REEs enriched, the middle REEs slightly depleted, and the heavy REEs and Y also slightly depleted but by less than the middle REEs. The elements Rb, K, Ba, Nb, Ta, and Pb are the most enriched, and are thus most incompatible during the evolution of the Redoubt system, while Cs behaves erratically, being either highly enriched or depleted relative to basalt. The variability in Cs contents is also seen other alkali elements, and presumably reflects variations in the composition of Cs in a crustal contaminant, as Cs is very incompatible and is almost completely excluded from crystallizing phases.

Most of the trace-elements and major-element patterns are qualitatively compatible with fractional crystallization, either in the chamber or on its walls. The variation in the REEs and Y suggests participation of hornblende in the fractionating assemblage, and indeed hornblende is present in the Holocene Redoubt Volcano andesites and dacites. Throughout most of the sample suite, Th, Pb and U appear incompatible, with apparent lesser enrichment of Th resulting in differences of Th/U and Th/Pb ratios between early and late magmas in the system (Fig. 15).

Variations in the high-field-strength elements Zr, Hf, Nb, and Ta are more complex, with Nb and Ta typically more enriched than Zr and Hf. Both hornblende and titanomagnetite have higher distribution coefficients for Nb and Ta than Zr or Hf, so that precipitation of these phases should result in a decrease in Nb/Zr and Ta/Hf ratios, rather than the observed increase. Also, no Zr-bearing phase was found in thin section. These systematics suggest a component of crustal contamination during Holocene petrogenesis.

Table 2
Geochemistry of representative samples of Redoubt Volcano eruptive deposits

	1966 dome		upper Drift River, ca. 250 yr B.P.						Crescent River, 3600–1800 yr B.P.		
	MSR-01	RDTJK-77	90CNR67i	90CNR64i	90CNR59	90CNR70	90CNR67	90CNR62	90CNR55	90CNR56	90CNR53B
SiO_2	60.12	60.30	50.53	58.93	59.75	60.98	62.51	63.22	58.46	58 93	58.93
TiO_2	0.562	0.554	1.121	0.638	0.578	0.499	0.495	0.467	0.598	0.578	0.611
Al_2O_3	18.52	18.40	17.43	18.31	18.57	18.68	18.12	17.88	18.87	18.92	18.55
FeO^t	5.86	5.82	10.64	5.94	5.75	5.45	4.64	4.60	6.36	6.09	6.35
MnO	0.142	0.145	0.158	0.144	0.144	0.146	0.131	0.129	0.151	0.147	0.149
MgO	2.37	2.28	6.35	3.14	2.58	1.75	2.01	1.76	2.71	2.57	2.72
CaO	6.75	6.72	9.75	7.27	6.97	6.54	5.95	5.69	7.43	7.29	7.25
Na_2O	4.03	4.09	3.04	4.02	4.04	4.21	4.29	4.35	3.95	3.97	3.97
K_2O	1.44	1.46	0.85	1.40	0.40	1.50	1.66	1.70	1.24	1.28	1.25
P_2O_5	0.219	0.215	0.135	0.204	0.219	0.244	0.201	0.195	0.227	0.229	0.220
Cs	0.17	0.18	0.33	0.63	0.98	1.03	1.04	0.85	0.12	0.42	0.68
Rb	29.27	29.87	13.60	26.61	26.84	29.14	31.68	33.90	23.34	25.46	22.24
Ba	596	607	317	561	578	624	667	696	520	535	519
Sr	519	513	419	489	520	547	498	498	511	509	508
La	11.54	11.64	7.17	11.91	11.54	12.63	13.22	13.74	10.94	11.29	11.12
Ce	22.67	23.06	15.49	23.46	23.12	24.96	26.08	26.69	22.42	22.98	22.51
Pr	2.78	2.86	2.22	2.92	2.90	3.16	3.16	3.16	2.87	2.91	2.90
Nd	11.89	11.99	10.87	12.58	12.45	13.62	12.94	13.00	12.53	12.72	12.76
Sm	2.92	2.93	3.27	3.15	3.11	3.25	3.04	2.94	3.22	3.17	3.25
Eu	0.96	1.01	1.13	1.00	1.00	1.04	0.97	0.94	1.05	1.07	1.06
Gdpo	2.67	2.86	3.47	3.05	2.89	2.96	2.77	2.83	3.02	3.16	3.04
Tb	0.46	0.47	0.60	0.49	0.49	0.50	0.46	0.44	0.52	0.50	0.52
Dy	2.89	2.91	3.81	3.04	3.02	3.12	2.86	2.65	3.30	3.07	3.20
Ho	0.60	0.60	0.78	0.63	0.62	0.64	0.59	0.55	0.68	0.63	0.67
Er	1.75	1.74	2.22	1.81	1.81	1.84	1.73	1.56	1.96	1.81	1.97
Tm	0.25	0.25	0.30	0.27	0.26	0.27	0.25	0.23	0.28	0.26	0.27
Yb	1.66	1.60	1.89	1.74	1.70	1.77	1.63	1.54	1.82	1.68	1.84
Lu	0.27	0.26	0.30	0.28	0.28	0.29	0.27	0.25	0.30	0.27	0.30
Y	16.46	16.50	20.39	17.26	17.60	17.46	16.38	15.15	18.02	16.95	18.53
Zr	115	116	85	113	115	122	128	130	114	116	115
Hf	2.50	2.33	1.92	2.26	2.32	2.61	2.36	2.15	2.55	2.09	2.54
Nb	5.50	5.47	3.53	4.97	5.31	5.76	5.94	5.64	4.90	4.66	4.76
Ta	0.33	0.33	0.20	0.27	0.32	0.37	0.42	0.32	0.27	0.27	0.28
Pb	6.24	6.20	3.54	5.50	5.83	6.22	6.69	7.22	5.50	4.84	4.92
Th	1.49	1.45	0.70	1.38	1.27	1.34	1.47	1.77	1.11	1.04	0.97
U	0.56	0.55	0.29	0.54	0.54	0.55	0.61	0.69	0.43	0.44	0.42
Ga	19	20	20	18	16	17	18	19	20	19	[illegible]
Cu	35	33	190	57	44	21	37	30	40	37	39
Zn	75	74	75	73	78	78	66	67	79	74	76
V	129	117	321	148	126	90	91	83	149	124	131
Sc	11	13	34	16	12	6	3	10	14	17	12
Cr	1	2	22	17	3	2	6	0	8	3	8
Ni	5	5	13	11	5	3	7	7	2	2	4
GMS	50.0	46.1	9.2	51.9	54.3	51.4	–	–	50.7	51.2	45.0
PLAG	39.7	44.7	47.8	37.2	37.2	40.3	–	–	41.0	39.2	45.7
HB	2.1	1.7	33.9	2.2	1.7	3.3	–	–	0.9	tr	0.1
HBRIM	–	0.3	–	0.9	0.1	–	–	–	–	0.8	–
OPX	2.2	2.1	0.9	2.4	1.0	1.7	–	–	1.0	1.9	2.6
CPX	1.4	2.2	4.7	2.6	1.4	0.7	–	–	3.2	2.7	2.7
OX	4.7	2.9	3.5	2.7	4.4	2.5	–	–	3.2	4.2	3.8
OL	–	–	–	0.1	–	–	–	–	–	–	

In addition to these general patterns, there were also some geochemical differences between magma batches erupted during each of the Holocene eruptive episodes (Fig. 15). The 1989–1990 magmas are distinct from all older magmas (except the slightly older pyroclastic samples from the Drift Glacier area) in that they have higher concentrations of large-ion lithophile ele-

			North flank pumice section, youngest at left						7800 yr B.P. pumice		
90CNR53A	90CNR51	90CNR54	90MR75-13	90MR75-10	90MR75-06A	90MR75-04	90MR75-02	90MR7041A	90MR70-01B	90CNR14
59.32	60.46	61.10	59.04	58.96	58.68	61.16	58.12	58.52	60.69	50.84
0.579	0.538	0.493	0.583	0.592	0.598	0.547	0.703	0.660	0.584	0.906
18.66	18.68	18.66	19.10	19.09	18.96	18.54	18.76	19.07	18.61	18.80
6.08	5.44	5.41	5.88	5.97	6.20	5.38	6.52	6.59	5.58	9.05
0.150	0.147	0.143	0.145	0.143	0.147	0.140	0.151	0.162	0.149	0.167
2.54	2.15	1.82	2.70	2.79	2.82	2.30	3.37	2.97	2.56	5.65
7.14	6.88	6.52	6.99	6.89	7.17	6.43	7.28	6.97	6.52	10.67
4.01	4.17	4.24	4.06	4.01	3.91	4.00	3.77	3.87	3.95	3.17
1.30	1.32	1.38	1.28	1.33	1.28	1.34	1.13	1.03	1.21	0.64
0.216	0.228	0.233	0.233	0.227	0.221	0.164	0.196	0.158	0.135	0.109
0.13	0.78	0.82	0.75	0.73	0.71	0.98	0.73	0.69	0.87	0.31
24.59	23.94	24.82	22.57	24.16	23.71	25.18	19.44	18.42	22.58	9.53
543	566	596	546	560	529	572	483	456	524	235
501	518	519	546	523	509	470	499	534	514	390
11.00	11.76	12.22	11.77	11.72	11.40	10.99	10.71	9.99	10.42	5.59
22.57	23.83	24.64	24.08	24.13	23.49	22.44	22.43	20.58	21.42	11.49
2.84	3.05	3.10	2.98	2.97	2.95	2.78	2.85	2.55	2.67	1.74
12.22	13.11	13.23	13.02	12.97	12.88	11.98	12.79	11.23	11.51	8.59
3.13	3.22	3.22	3.25	3.28	3.18	3.02	3.26	2.91	2.96	2.68
1.03	1.03	1.06	1.00	1.05	0.99	1.00	1.04	1.04	1.02	0.97
2.97	3.00	2.97	2.91	2.93	2.96	2.85	3.12	2.69	2.73	2.96
0.52	0.50	0.50	0.49	0.50	0.50	0.48	0.52	0.46	0.48	0.53
3.18	3.11	3.09	3.10	3.17	3.10	3.03	3.21	2.92	2.98	3.44
0.65	0.63	0.63	0.62	0.65	0.64	0.61	0.66	0.61	0.62	0.74
1.93	1.87	1.84	1.82	1.91	1.88	1.82	1.93	1.77	1.83	2.09
0.27	0.26	0.27	0.26	0.27	0.27	0.26	0.27	0.25	0.26	0.28
1.79	1.74	1.76	1.70	1.76	1.75	1.76	1.77	1.70	1.78	1.81
0.30	0.30	0.29	0.28	0.29	0.29	0.29	0.30	0.28	0.30	0.29
17.42	18.18	17.52	17.29	17.86	17.99	17.61	18.16	16.73	17.26	18.80
116	119	124	119	124	120	120	114	120	120	64
2.58	2.55	2.64	2.63	2.74	2.60	2.63	2.53	2.65	2.72	1.35
4.87	6.30	5.15	4.49	4.56	4.21	4.18	3.70	4.62	4.40	1.18
0.27	0.61	0.30	0.25	0.25	0.25	0.25	0.22	0.26	0.25	0.08
5.73	5.36	5.60	6.03	5.77	5.37	6.09	5.39	6.39	5.85	2.70
1.19	1.03	1.03	1.23	1.12	1.05	1.32	1.27	1.11	1.19	0.89
0.47	0.47	0.42	0.53	0.47	0.46	0.63	0.56	0.49	0.59	0.32
20	18	19	18	19	21	18	19	20	21	19
37	24	17	43	67	56	31	56	32	27	130
76	78	71	77	80	80	69	76	87	79	75
124	107	85	132	127	127	110	154	132	102	333
18	11	11	13	13	16	14	19	14	11	41
6	0	4	4	5	5	5	7	2	4	43
4	4	5	7	4	4	4	10	5	7	11
57.5	57.2	63.6	–	–	–	–	–	–	–	45.8
32.6	33.4	27.5	–	–	–	–	–	–	–	39.0
0.7	1.7	6.1	–	–	–	–	–	–	–	0.0
–	1.1	–	–	–	–	–	–	–	–	–
3.1	1.2	0.6	–	–	–	–	–	–	–	0.0
2.8	2.8	0.5	–	–	–	–	–	–	–	9.5
3.3	2.8	1.7	–	–	–	–	–	–	–	1.7
–	–	–	–	–	–	–	–	–	–	3.9

Modes based on 1000 optical determinations by V.F. Avery.
Major oxides and Sr, Zr, Ga, Cu, Zn, V, Sc, Cr, and Ni determined by XRF at Washington State University.
Cs, Rb, Ba, REE, Y, Nb, Hf, Ta, U, Th, and Pb determined by ICP/MS at Washington State University.
Analytical precision in Nye et al., 1994-this volume.

ments (LILE) and Th. The ca. 250-yr-old Drift Glacier magma is distinct from 1989–1990 deposits in having lower Cs content, higher TiO_2, lower FeO_t/MgO, and lower Al_2O_3. Mafic inclusions in the Drift Glacier deposit have higher V and Zr and lower Sr than inclusions from the 1989–1990 deposits.

The still older Crescent River magmas have LILE concentrations intermediate between younger and older magmas, and are also unlike

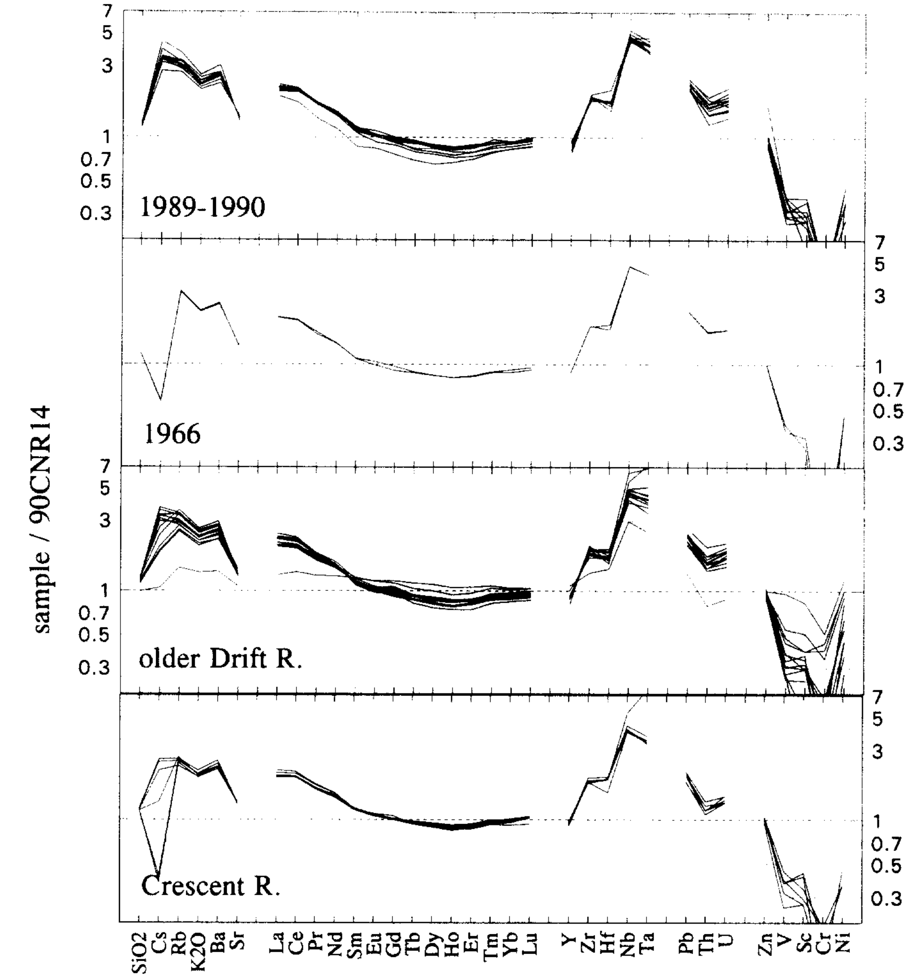

Fig. 14. Trace-element concentrations of Holocene magmas from Redoubt Volcano normalized to 90CNR14, an olivine-clinopyroxene-bearing basalt from the north flank of Redoubt Volcano. Note the general similarity of all samples, the extreme variations in Cs and Rb/Cs, and the greater enrichment of Nb and Ta compared to Zr and Hf.

the Drift River magmas in their low TiO_2, U, and Th, and high FeO_t/MgO ratios. Variations in Cs and Zr among the samples is thought to reflect crustal contamination. In contrast, variation in Al_2O_3 and Sr may reflect fractionation of plagioclase during magma evolution, and variations in TiO_2 and FeO/MgO and V presumably reflect variations in the amount of magnetite.

These chemical patterns indicate that batches of Redoubt Volcano magma involved in the successive Holocene eruptive episodes cannot be simply related by shallow-level evolution to each other or to a common parent, either by fractional crystallization or by some other constant series of processes. Holocene magma bodies were affected by crustal contamination, and were probably also modified by new influxes of mafic magma.

The overall change from voluminous eruptions of mafic lavas during the Pleistocene to more silicic lavas during the Holocene may reflect long-term chemical evolution of the magmatic system, or a change in the physical controls on eruptive processes. Similar patterns have been observed at many volcanoes around the world, suggesting that increasing cone height

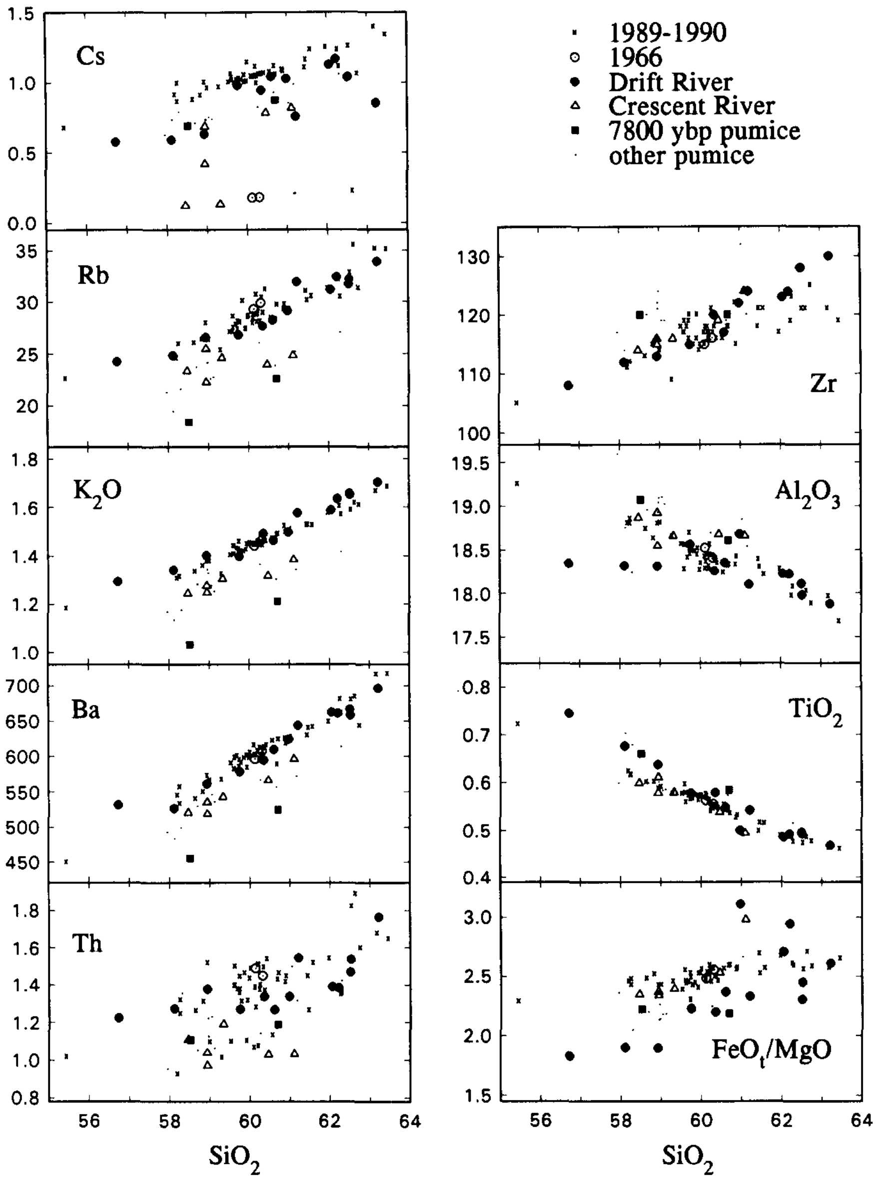

Fig. 15. SiO_2 variation diagrams showing aspects of major- and trace-element chemistry that allow separation of rocks from different eruptive episodes at Redoubt Volcano.

during the life of a volcano favors the eruption of less dense and more silicic magmas (Rose et al., 1977; Gill, 1981).

4. Implications for future hazards at Redoubt Volcano

Reconstructions of volcanic eruption histories may reveal patterns in eruptive behavior and indicate hazards likely be associated with future eruptions (Crandell et al., 1979; Begét and Kienle, 1992). The sequence of postglacial eruptive deposits at Redoubt Volcano indicates that a series of shifts have occurred in the style and focus of volcanism. The earliest postglacial eruptive event was the emplacement of the Harriet Point debris avalanche in Redoubt Creek sometime between 10,500 and 13,000 yr B.P. (Fig. 16). Tephras were repeatedly erupted during the early Holocene (Fig. 17). Riehle (1985) reported almost two dozen ash layers in a core from a lake located about 25 km east of Redoubt Volcano, and we observed multiple layers of fine ash and several thick lapilli layers in peat and soil sections near Redoubt Creek and Drift River. We obtained radiocarbon dates of 7730±160, 6660±90, 6340±80 and 4840±70 yr B.P. on peat adjacent to some of the thickest lapilli layers (Table 1). However, no pyroclastic flows or lahars of early Holocene age have been recognized on the flanks of Redoubt Volcano.

The Crescent River lahars, emplaced about 3600 yr B.P., record collapse and mobilization of hydrothermally altered material from the southern flank of Redoubt Volcano. Eruptions continued to affect the upper Crescent River area for at least another 1500 years, as exposures along the North Fork of the Crescent River reveal several lahars that are apparently composed of reworked pyroclastic debris. Recent flood deposits and the Rust Slough lahar record a final shift of the focus of volcanism to the Drift River valley. The Rust Slough lahar consists of hydrothermally altered debris that travelled more than 30 km downvalley to the area of the Drift River Terminal prior to ca. 250 years ago. Several prehistoric flood deposits overlie the yellow clayey lahar in Rust Slough, and resemble sediments produced by the 1989–1990 eruptions. These deposits, together

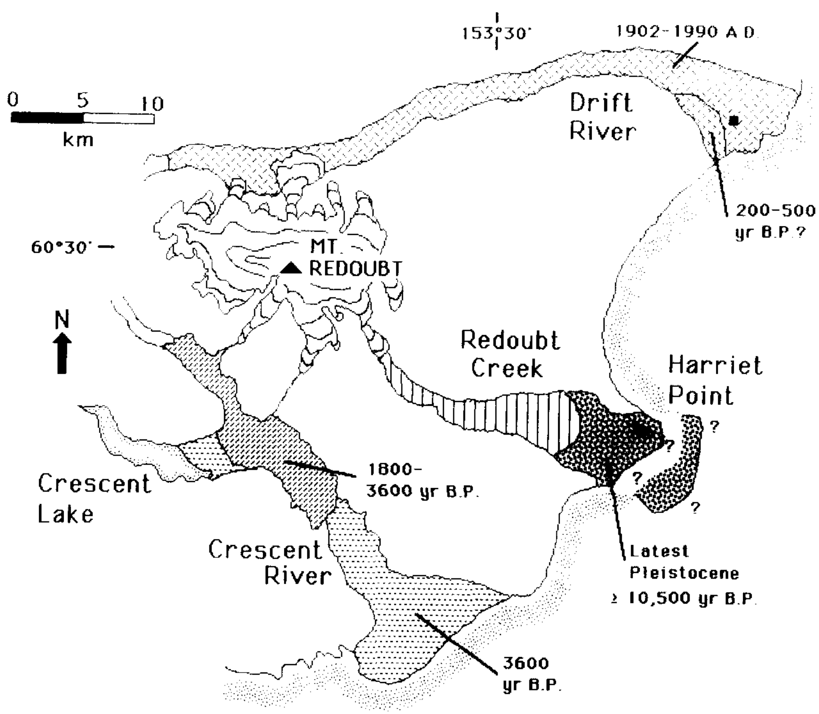

Fig. 16. Age and extent of postglacial volcanic flowage deposits of different age preserved on the flanks of Redoubt Volcano. Vertically lined pattern in Redoubt Creek drainage shows area of non-volcanic glacial and alluvial deposits which postdate the Harriet Point Debris Avalanche. Note that deposits from recent volcanic activity (i.e., during the last millenium) are entirely confined to the Drift River Valley.

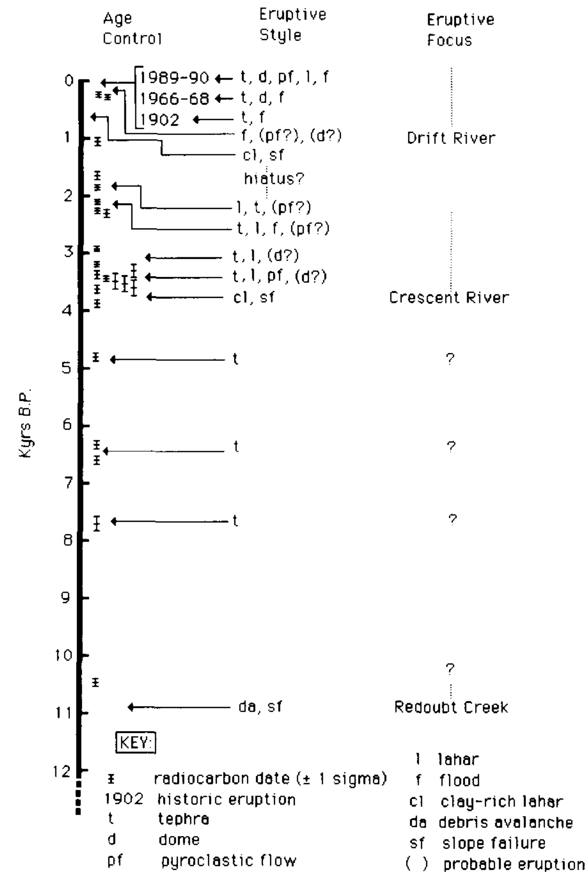

Fig. 17. Sequence of eruptive events in postglacial time recorded by deposits preserved around Redoubt Volcano.

with those of the 1902 eruption, the 1966 and 1989–1990 eruptions, record a series of debris flows and floods that have repeatedly affected the lower Drift River fan during the last several hundred years.

The history of volcanic eruptions determined for Redoubt Volcano clearly becomes increasingly fragmentary with increasing age. However, even though incomplete, the partial record of the postglacial eruptive activity of Redoubt Volcano provides some important insights into the behavior of this volcano and the frequency of different types of volcanic eruptions. These data can be used to evaluate the likely hazards from future eruptions of Redoubt Volcano.

4.1. Debris avalanches

Hazard planning for large volcanic debris avalanches must take into account their great mobility. The Harriet Point debris avalanche travelled at least 30 km from Redoubt Volcano to the modern shoreline of Cook Inlet, and total travel distance may have been 35 km or more. The ratio of height loss (H) to total runout distance (L) of debris avalanches is typically about 0.1, with avalanches of volume greater than 1 km^3 having H/L ratios that are slightly smaller (Siebert et al., 1987). The late Pleistocene elevation of Redoubt Volcano is not known, but if it was similar to the modern summit height, i.e., about 3000 m, then H/L for the Harriet Point debris avalanche was ca. 0.1–0.09 (Fig. 18). If a future eruption produces a debris avalanche as large and mobile as the Harriet Point deposit, it will likely travel ca. 30–35 km downvalley, and could bury the entire width and length of either the Drift River, Redoubt Creek, or the Crescent River valleys.

Such an avalanche might also travel several kilometers into Cook Inlet. A debris avalanche in 1883 from Mount St. Augustine entered the sea and formed tsunami waves that were as much as 20 m high near the volcano, and about 10 m high after travelling 80–100 km across Cook Inlet (Kienle et al., 1987; Siebert et al., 1989). The

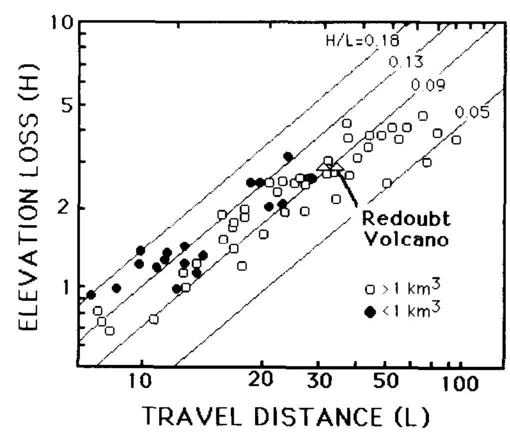

Fig. 18. Plot of ratio of total elevation loess (H) versus total horizontal travel distance for Harriet Point debris avalanche and other large debris avalanches. Modified from Siebert (1984).

generation of tsunami waves in upper Cook Inlet might cause damage and destruction to offshore oil platforms and the coastal towns of the Kenai Peninsula, in areas far removed from the flanks of Redoubt Volcano.

The likelihood of another debris avalanche at Redoubt Volcano in the near future is probably very small, as there has been only one such event during the last 10,500 years. However, Redoubt Volcano should be monitored during future eruptions for signs of edifice deformation and incipient summit collapse and debris avalanche formation.

4.2. Pyroclastic flows

Prior to the 1989–1990 Redoubt Volcano eruptions, the potential hazard due to pyroclastic flows from Redoubt Volcano seemed minimal. Prehistoric pyroclastic flow deposits had only been recognized on the immediate flanks of Redoubt Volcano, and all were pre-Holocene in age (Brantley, 1990; Till et al., 1990). However, pyroclastic flows were repeatedly generated during the 1989–1990 eruptions, and one ash cloud travelled more than 13 km north from the summit dome of Redoubt Volcano (Brantley, 1990).

The prehistoric eruption history of Redoubt Volcano provides additional evidence that pyroclastic flows constitute a significant potential hazard in valley bottoms near the volcano. The Crescent Glacier pyroclastic fan in the Crescent River valley on the south flank of Redoubt Volcano contains more than a dozen lithic pyroclastic flows at a distance of 10 km from the modern summit. A lahar in the Crescent River assemblage some 15 km downvalley from the summit contains some breadcrust bombs and prismatically jointed blocks, suggesting that some of its clasts were still hot when the flow was emplaced.

It is clear that significant hazards from pyroclastic flows exist during eruptions for distances of 10–15 km from the summit of Redoubt Volcano, particularly on the northern side of the volcano.

4.3. Lahars and floods

Two types of lahar deposits are preserved along valley floors around Redoubt Volcano. Clay-rich lahars, generated by massive slope failures of hydrothermally altered and water-saturated sediments on the volcano, have been formed during at least two separate intervals. At least two lahars of this type travelled more than 30 km down the Crescent River ca. 3600 years ago. A clay-rich lahar, found 30 km down the Drift River valley, is less than 1000 years old, and probably formed about 300–400 years ago. The north-facing summit basin of Redoubt Volcano may be the scar of this recent episode of collapse.

Extensive zones of hydrothermally altered rock at volcano summits are created by fumarolic and hydrothermal alteration; such areas are especially prone to slope failures during eruptions. Geologic mapping suggests that the summit rocks presently exposed on the rim of the central basin or crater of Redoubt Volcano are not highly altered, although an extensive altered exists on the east flank on Redoubt Volcano at the head of Redoubt Creek (Till et al., 1990).

The second type of debris flow found at Redoubt Volcano is composed almost entirely of fragmental monolithic debris and was probably generated by the interaction of domes or pyroclastic flows with snow and ice on the volcano slopes, as occurred in 1966 and 1989–1990. Lahars and floods produced during these historic eruptions were channelled down the Drift River valley and then debouched across the lower fan in the area of the Drift River Terminal. It seems likely that future eruptions of Redoubt Volcano, even if brief or small, have a high probability of generating floods and lahars of similar extent.

4.4. Recent eruptive patterns and future volcanic hazards

Volcanic deposits preserved on the flanks of Redoubt Volcano indicate that small pyroclastic eruptions and coeval flooding have occurred frequently during the late Holocene. Pyroclastic flows, lahars, and flood deposits in the Crescent River drainage record an early eruptive sequence that seems quite similar to the historic activity in the Drift River valley. Nine radiocarbon dates on the monolithic North Fork lahars in the Crescent River drainage suggest that intermittent eruptions on the south flank of the volcano continued for at least 1800–2000 years after an initial slope failure, but do not allow a precise estimate of eruption frequency.

In the Drift River drainage, a prehistoric edifice collapse recorded by the Rust Slough Lahar was followed by at least 5–6 additional eruptions that produced pyroclastic flows, widespread airfall ash deposits, lahars, and floods. Redoubt Volcano has erupted three times just in the 20th century. The current series of pyroclastic eruptions in the Drift River, if sustained for as long the Crescent River sequence, could continue for hundreds or even thousands of years into the future. While the frequency of prehistoric eruptions cannot be precisely determined, the pattern of historic and prehistoric eruptions during the last several hundred suggests the Redoubt Volcano is likely to erupt again in the next 25–100 years. If future eruptions generate domes in the same area of the summit as did the 1966 and 1989–1990 eruptions, future pyroclastic flows, lahars, and floods will continue to be localized on the north side of the volcano.

Acknowledgments

We would like to acknowledge the assistance and hospitality of the staff of the Drift River Terminal, who graciously allowed us to stay at the tank farm during our field work. We also thank the pilots of Alaska Helicopter. We extend special thanks to Dr. Tom Miller, Tina Neal, Cynthia Gardner, and the other AVO-Anchorage staff for their oversight and logistical coordination efforts through the Redoubt Volcano eruptions and the following summer field season. Careful reviews by Dr. Richard Waitt and Dr. Allison Till greatly improved this manuscript. This work was funded by the Alaska Volcano Observatory, a joint operation of the U.S. Geological Survey, the University of Alaska, and the Alaska Division of Geological and Geophysical Surveys.

References

Begét, J., 1981. Recent volcanic activity at Glacier Peak. Science, 215: 1389–1390.

Begét, J., 1983. Glacier Peak, Washington: A potentially hazardous Cascade volcano. Environ. Geol., 5: 83–92.

Begét, J. and Kienle, J., 1992. Cyclic formation of debris avalanches at Mount St Augustine Volcano. Nature, 356: 701–704.

Begét, J. and Nye, C., 1990. Extent of prehistoric debris avalanches and lahars from Mt. Redoubt, Alaska. EOS, Trans. Am. Geophys. Union, 71: 1706.

Begét, J., Stihler, S. and Stone, D., 1994. A 500-year-long record of tephra falls from Redoubt Volcano and other volcanoes in upper Cook Inlet, Alaska. In: T.P. Miller and B.A. Chouet (Editors), The 1989–1990 Eruptions of Redoubt Volcano, Alaska. J. Volcanol. Geotherm. Res., 62: 55–67.

Brantley, S.R. (Editor), 1990. The Eruption of Redoubt Volcano, Alaska, December 14, 1989–August 31, 1990. U.S. Geol. Surv., Circ. 1061, 33 pp.

Crandell, D.R., 1971. Postglacial Lahars from Mount Rainier Volcano, Washington. U.S. Geol. Surv., Prof. Pap. 667, 75 pp.

Crandell, D.R., Mullineaux, D.R. and Rubin, M., 1975. Mount St. Helens volcano: recent and future behavior. Science, 187: 438–441.

Crandell, D.R., Mullineaux, D.R. and Miller, C.D., 1979. Volcanic-hazards studies in the Cascade Range of the western United States. In: P.D. Sheets and D.K. Grayson (Editors), Volcanic Activity and Human Ecology. Academic Press, New York, NY, pp. 195–219.

Flint, R.F., 1971. Glacial and Quaternary Geology. Wiley, New York, NY, 892 pp.

Gill, J.B., 1981. Orogenic Andesites and Plate Tectonics. Springer-Verlag, New York, NY, 390 pp.

Glicken, H., 1991. Rockslide-debris Avalanche of May 18, 1980, Mount St. Helens volcano, Washington. U.S. Geol. Surv., Prof. Pap. 1488, 304 pp.

Hamilton, T.D. and Thorson, R.M., 1983. The Cordilleran ice sheet in Alaska. In: S.C. Porter (Editor), The Late Pleistocene, V. 1 of H.E. Wright, Jr. (Editor), Late Quaternary Environments of the United States. University of Minnesota Press, Minneapolis, MN, pp. 38–52.

Kienle, J., Kowalik, Z. and Murty, T.S., 1987. Tsunamis generated by eruptions from Mount St. Augustine volcano, Alaska. Science, 236: 1442–1447.

Nye, C.J. and Turner, D.L., 1990. Petrology, geochemistry, and age of the Spurr volcanic complex, eastern Aleutian arc. Bull. Volcanol., 52: 205–226.

Post, A. and Mayo, L., 1971. Glacier-dammed lakes and outburst floods in Alaska. U.S. Geol. Surv., Hydrol. Inv. Atlas HA-455.

Riehle, J.R., 1985. A reconnaissance of the major Holocene tephra deposits in the upper Cook Inlet region, Alaska. J. Volcanol. Geotherm. Res., 26: 37–74.

Riehle, J.R. and Emmel, K.S., 1980. Photointerpretation map of the surficial geology, Polly Creek to McArthur River, Cook Inlet, Alaska. Alaska Div. Geol. Geophys. Surv., Geol. Rep. 64, 2 sheets, scale 1:63,360.

Riehle, J.R., Kienle, J. and Emmel, K.S., 1981. Lahars in Crescent River valley, lower Cook Inlet, Alaska. Alaska Div. Geol. Geophys. Surv., Geol. Rep. 53, 10 pp.

Rose Jr., W.I., Grant, N.K., Hahn, G.A., Lange, I.M., Powell, J.L., Easter, J. and DeGraff, J.M., 1977. The evolution of Santa Maria volcano, Guatemala. J. Geol., 85: 63–87.

Schmoll, H.R. and Yehle, L.A., 1986. Pleistocene glaciation of the upper Cook Inlet basin. In: T.D. Hamilton, K.M. Reed and R.M. Thorson (Editors), Glaciation in Alaska, the Geologic Record. Alaska Geological Society, Anchorage, AK, pp. 193–218.

Schmoll, H.R., Szabo, B.J., Rubin, M. and Dobrovolny, E., 1972. Radiometric dating of marine shells from the Bootlegger Cove clay, Anchorage area, Alaska. Geol. Soc. Am. Bull., 83: 1107–1113.

Siebert, L., 1984. Large volcanic debris avalanches: characteristics of source areas, deposits, and associated eruptions. J. Volcanol. Geotherm. Res., 22: 163–197.

Siebert, L., Glicken, H. and Ui, T., 1987. Volcanic hazards from Bezymianny- and Bandai-type eruptions. Bull. Volcanol., 49: 435–459.

Siebert, L., Glicken, H. and Kienle, J., 1989. Debris avalanches and lateral blasts at Mt. St. Augustine Volcano, Alaska. Nat. Geogr. Res., 5: 232–249.

Sturm, M., Benson, C. and MacKeith, P., 1986. Effects of the 1966–68 eruptions of Mt. Redoubt on the flow of Drift Glacier. J. Glaciol., 32: 355–362.

Sturm, M., Begét, J. and Benson, C., 1987. Observations of jokulhlaups from ice-dammed Strandline Lake, Alaska: implications for paleohydrology. In: L.Mayer and D. Nash (Editors) Catastrophic Flooding. Allen and Unwin, Boston, MA, pp. 79–94

Swanson, S. and Kienle, J., 1988. The 1986 eruption of Mount St. Augustine: field test of a hazard evaluation. J. Geophys. Res., 93: 4500–4520.

Till, A.B., Yount, E. and Riehle, J.R., 1990. Redoubt Volcano, Cook Inlet, Alaska: a hazard assessment based on eruptive activity through 1968. U.S. Geol. Surv., Open-File Rep. 90-246, 33 pp.

Ui, T., 1983. Volcanic dry avalanche deposits — identification and comparison with non-volcanic debris stream deposits. J. Volcanol. Geotherm. Res., 22: 135–150.

Ui, T. and Glicken, H., 1986. Internal structural variations in a debris-avalanche deposit from ancestral Mount Shasta, California, USA. Bull. Volcanol., 48: 189–194.

Ui, T., Yamamoto, H. and Suzuki-Kamata, K., 1986. Characterization of debris avalanche deposits in Japan. J. Volcanol. Geotherm. Res., 29: 231–243.